Factory Automation Project Selection Using Multicriterion Q-Analysis

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ABSTRACT

This paper demonstrates the use of MCQAII, as a multicriterion decision-making tool, to choose automation projects for the printed-circuit-board manufacturing business. Q-analysis is used to group alternatives at different levels of satisfaction. A new eccentricity index can measure the relationships between alternatives. In addition, the conjugate complex, which transposes the alternative-criterion matrix, is analyzed to rank the decision criteria and examine the relationships between them. The results are compared with the ELECTRE I multicriterion algorithm. These techniques are used to show how both quantifiable and nonnumerical criteria (which represent short- and long-term objectives), chosen to enhance a company's strategic position, can be used to select optimal alternatives.

INTRODUCTION

It is imperative for manufacturing facilities to incorporate state-of-the-art processes and equipment in their businesses to stay globally competitive and satisfy customer expectations. Many potential improvement projects are difficult to justify because of the high installation costs and intangible benefits. Ignoring intangible benefits, however, has left many domestic manufacturers behind their international competitors.

This paper shows the potential benefits of incorporating multicriterion decision-making techniques in justifying automation projects for manufacturing facilities because alternatives with conflicting quantitative and nonnumerical measures can be compared. Quantitative measures are the traditional

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short-term indicators such as return on investment and payback period. The nonnumerical concerns are issues such as quality, competitiveness, and production flexibility. Decision makers in manufacturing management should pay attention to these factors as well as short-term factors.

One decision-making tool is MCQAII, an analytical technique that can incorporate quantitative and nonnumerical factors into a framework that helps select the optimum alternative [7]. The technique ranks alternatives with respect to a set of criteria by utilizing satisfaction, concordance, and discordance indices.

An example of an MCQAII application in the printed-circuit-board industry is used to examine the importance of an individual criterion to the criterion set. This is done by grouping criteria, measuring the strength of the interactions between groups, and measuring the effect criteria have on distinguishing alternatives from one another. The ranking of alternatives from MCQAII is compared with ranking from ELECTRE I.

DECISION-MAKING CRITERIA

Manufacturing managers have traditionally relied on short-term measures of profitability to justify capital expenditures for automation. Examples of short-term measures include internal rate of return, net present worth, and payback years. These classical engineering economic parameters do not provide measures for long-term strategic planning. Managers must be willing to consider other, nonmonetary factors in their decisions [2].

The following factors are examples of long-term issues for strategic planning of a manufacturing facility when considering automation. These are some of the nonnumerical benefits that managers should optimize in future planning for the firm:

1. Market position.
2. Growth potential.
3. Customer-service improvements.
4. Profitability and value added gained by automation.
5. Cash flow, including startup, installation, fixed, sunk, and maintenance costs.
6. Resource utilization.
7. Investment risk.
8. Technical assessment.
9. Shop productivity.
10. Reduction of manufacturing lead time.
11. Increase of material turnover.
12. Reduction of inventory.
13. Increase of employee involvement and commitment.

For the specific example in this paper, the following criteria for choosing investment alternatives and automation projects were selected. (+) indicates that the criterion is to be maximized; (−) indicates that the criterion is to be minimized:

C1	(+)	Internal rate of return
C2	(−)	Investment risk
C3	(+)	Competitive edge
C4	(+)	Quality improvement
C5	(+)	Flexibility improvement
C6	(+)	Cross applicability
C7	(−)	Learning curve (months)
C8	(+)	Management commitment

Criteria 2, 3, 8 are rated on a scale of high, medium, and low. Criteria 4, 5, 6 are rated on a scale of very high, high, medium, low, and very low. Criterion 7 is expressed as the number of months needed to implement the automated process.

The following weights are given to the above criteria as a measure of the relative importance of each criterion to choosing the best alternative. (3) indicates most important and (1) indicates least important:

Criteria	Weight
C1	3
C2	2
C3	3
C4	3
C5	1
C6	1
C7	1
C8	2

DECISION ALTERNATIVES

Twelve project alternatives are compared in a project impact matrix for the printed-circuit-board (PCB) industry [1, 5, 8]:

A1 *Automated PCB photoprocessing* automates material handling and photoprocessing of PCBs with conveyors and robots.

A2 *Automated PCB plating-bath control* monitors chemical concentrations and maintains the chemical contents of the process baths. Statistical process control is used in this operation with the continuous monitoring of process variables. This alternative uses sensors, actuators, and a distributed computer network.

A3 *Automated printed-wiring-board optical inspection* uses x-rays to inspect multilayers, artwork, and photoresist in a nondestructive test.

A4 *Automated PCB identification* uses a robot and laser technology to inscribe identification codes on the PCBs. This reduces accounting errors and cycle time, and increases inventory turnover.

A5 *Automated component preparation* automates the process of pretinning component wires.

A6 *Automated component kitting* sorts components into individual kits for each PCB. This alternative uses a computer driven sorting and material handling system.

A7 *Automated component insertion* uses robots to position, bend, and cut leads.

A8 *Automated masking* uses a robot with a vision system to apply a solder mask to holes and sensitive components before the wave soldering process.

A9 *Automated presolder inspection* uses a vision system to verify correct placement of components on the PCB.

A10 *Automated point solder* uses a robot to hand-solder components too sensitive for wave soldering.

A11 *Automated solder joint inspection* checks the solder joints on the PCB. This alternative uses an x-ray system.

A12 *Do nothing* —do not implement any automation project.

MCQAII ANALYSIS

The first step of MCQAII is to set up the project impact matrix (Table 1), which ranks the alternatives to the set of criteria [7]. This is done with the original scales described in the "Decision-Making Criteria" section.

The nonnumerical values are given new values in nonlinear value functions, and the reciprocals of the numbers of implementation months is given, so that all the ratings will be maximized (Table 2).

The project impact matrix is used to compute a preference matrix, or project value matrix (Table 3). The new elements are defined by the

TABLE 1
PROJECT IMPACT MATRIX

	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.71	M	M	L	H	M	6	M
A2	0.73	H	H	M	VH	H	8	M
A3	0.73	L	M	H	M	L	6	H
A4	0.22	M	M	L	M	H	3	M
A5	1.34	M	M	M	M	H	6	L
A6	0.63	M	H	M	VH	VH	6	M
A7	1.51	M	H	M	VH	VH	6	M
A8	0.67	M	M	M	M	H	3	M
A9	0.42	H	H	VH	H	H	6	M
A10	0.54	M	M	M	M	H	6	M
A11	0.45	H	H	H	H	L	12	H
A12	0.00	L	L	VL	VL	M	0	M

following equation:

$$U(p(i,j)) = \frac{p(i,j) - p_{\min}(j)}{p_{\max}(j) - p_{\min}(j)}, \tag{1}$$

where

i = alternatives $1, \ldots, 12$,
j = criteria $1, \ldots, 8$,
$p_{\min}(j)$ = minimum element of column j,
$p_{\max}(j)$ = maximum element of column j.

TABLE 2
PROJECT IMPACT MATRIX—QUANTIFIED

	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.71	0.40	0.60	0.35	0.96	0.40	0.17	0.68
A2	0.73	0.30	0.90	0.55	0.99	0.48	0.11	0.80
A3	0.73	0.95	0.60	0.70	0.80	0.30	0.17	0.95
A4	0.22	0.60	0.61	0.50	0.80	0.50	0.33	0.55
A5	1.34	0.60	0.51	0.52	0.80	0.60	0.17	0.20
A6	0.63	0.60	0.99	0.55	0.95	1.00	0.17	0.60
A7	1.51	0.70	1.00	0.58	0.99	1.00	0.17	0.80
A8	0.67	0.50	0.50	0.60	0.70	0.70	0.33	0.60
A9	0.42	0.90	0.80	1.00	0.90	0.80	0.17	0.83
A10	0.54	0.40	0.50	0.53	0.75	0.65	0.17	0.70
A11	0.45	0.10	0.95	0.75	0.92	0.30	0.08	0.99
A12	0.00	1.00	0.05	0.10	0.01	0.09	1.00	0.05

TABLE 3
PREFERENCE MATRIX

	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.47	0.14	0.58	0.00	0.97	0.14	0.10	0.61
A2	0.48	0.00	0.89	0.31	1.00	0.26	0.03	0.76
A3	0.48	0.93	0.58	0.54	0.81	0.00	0.10	0.95
A4	0.15	0.43	0.59	0.23	0.81	0.29	0.27	0.44
A5	0.89	0.43	0.48	0.26	0.81	0.43	0.10	0.00
A6	0.42	0.43	0.99	0.31	0.96	1.00	0.10	0.51
A7	1.00	0.57	1.00	0.35	1.00	1.00	0.10	0.76
A8	0.44	0.29	0.47	0.38	0.70	0.57	0.27	0.51
A9	0.28	0.86	0.79	1.00	0.91	0.71	0.10	0.80
A10	0.36	0.14	0.47	0.28	0.76	0.50	0.10	0.63
A11	0.30	−0.29	0.95	0.62	0.93	0.00	0.00	1.00
A12	0.00	1.00	0.00	−0.38	0.00	−0.30	1.00	−0.19

The analysis was performed with different sets of slicing parameters,

$$\alpha(k) = \alpha k, \qquad k = 1, 2, \ldots, K.$$

Here K represents the number of satisfaction levels. MCQAII will compute the K incidence matrices, one for each level:

Density	α	k	$\alpha(k)$
Moderate	0.1	$1,\ldots,9$	$0.1, 0.2, \ldots, 0.9$
Sparse	0.25	$1,2,3$	$0.25, 0.50, 0.75$
Dense	0.05	$1,\ldots,19$	$0.05, 0.10, 0.15, \ldots, 0.90, 0.95$

An example of the incidence matrices is given in Table 4 for the sparse density set. The rule for creating the matrix is as follows:

$$b(i,j) = \begin{cases} 1 & \text{if} \quad U(p(i,j)) \geqslant \alpha(k), \\ 0 & \text{otherwise}. \end{cases} \tag{2}$$

Three other indices are computed from the incidence matrices:

I. PSI(i), *project satisfaction index*. This represents how well an alternative i satisfies various criteria j at the different slicing levels k:

$$\text{PSI}(i) = \sum_{(j,k)} w(j) b(i,j) \alpha(k). \tag{3}$$

TABLE 4

	C1	C2	C3	C4	C5	C6	C7	C8
				$\alpha_2(1) = 0.25$				
A1	1	0	1	0	1	0	0	1
A2	1	0	1	1	1	1	0	1
A3	1	1	1	1	1	0	0	1
A4	0	1	1	0	1	1	1	1
A5	1	1	1	1	1	1	0	0
A6	1	1	1	1	1	1	0	1
A7	1	1	1	1	1	1	0	1
A8	1	1	1	1	1	1	1	1
A9	1	1	1	1	1	1	0	1
A10	1	0	1	1	1	1	0	1
A11	1	0	1	1	1	0	0	1
A12	0	1	0	0	0	0	1	0
				$\alpha_2(2) = 0.50$				
A1	0	0	1	0	1	0	0	1
A2	0	0	1	0	1	0	0	1
A3	0	1	1	1	1	0	0	1
A4	0	0	1	0	1	0	0	0
A5	1	0	0	0	1	0	0	0
A6	0	0	1	0	1	1	0	1
A7	1	1	1	0	1	1	0	1
A8	0	0	0	0	1	1	0	1
A9	0	1	1	1	1	1	0	1
A10	0	0	0	0	1	1	0	1
A11	0	0	1	1	1	0	0	1
A12	0	1	0	0	0	0	1	0
				$\alpha_2(3) = 0.75$				
A1	0	0	0	0	1	0	0	0
A2	0	0	1	0	1	0	0	1
A3	0	1	0	0	1	0	0	1
A4	0	0	0	0	1	0	0	0
A5	1	0	0	0	1	0	0	0
A6	0	0	1	0	1	1	0	0
A7	1	0	1	0	1	1	0	1
A8	0	0	0	0	0	0	0	0
A9	0	1	1	1	1	0	0	1
A10	0	0	0	0	1	0	0	0
A11	0	0	1	0	1	0	0	1
A12	0	1	0	0	0	0	1	0

Normalizing before ranking,

$$\text{PSIN}(i) = \frac{\text{PSI}(i)}{\text{PSIMAX}}.$$

This does not involve comparisons with other alternatives.

II. PCI(i), *project comparison index*. This represents a relative ranking of the alternatives. It concerns the difference between the maximum number of satisfied criteria ($Q_{\max}$) and the next highest number of satisfied criteria (Q^*) satisfied by any other alternative at the same slicing level:

$$\text{PCI}(i) = \sum_k \alpha(k)\left[Q_{\max}(i,k) - Q^*(i,k)\right]. \tag{4}$$

Normalizing,

$$\text{PCIN}(i) = \frac{\text{PCI}(i)}{\text{PCIMAX}}.$$

III. PDI(i), *project discordance index*. This represents the discomfort a decision maker feels in accepting an alternative which has unsatisfied criteria. PDI is computed from complementary incidence matrices $b^*(k)$ for each level k:

$$b_k^*(i,j) = \begin{cases} 1 & \text{if} \quad b_k(i,j) = 0, \\ 0 & \text{if} \quad b_k(i,j) = 1, \end{cases}$$

$$\text{PDI}(i) = \sum_K \alpha(k)\left[Q_{\max}(i,k) - Q^*(i,k)\right]. \tag{5}$$

A high PDI indicates that there is much discomfort when choosing an alternative with some unsatisfied criteria. Normalizing,

$$\text{PDIN}(i) = \frac{\text{PDI}(i)}{\text{PDIMAX}}.$$

OTHER INDICES

IV. PRI1, *project rating index*. PSI and PCI could be in conflict, since PSI measures the number of criteria that one alternative satisfies and PCI measures the relative number of criteria satisfied by one alternative compared to other alternatives at various slicing levels. So these two indices can be combined with an L_p norm:

$$\mathrm{PRI1}(i) = \left(|1-\mathrm{PSIN}(i)|^P + |1-\mathrm{PCIN}(i)|^P\right)^{1/P}. \tag{6}$$

V. PRI2, *project rating index including discordance*. One may use an L_p norm and rank the alternatives by ascending values of the norm:

$$\mathrm{PRI2}(i) = \left(|1-\mathrm{PSIN}(i)|^P + |1-\mathrm{PCIN}(i)|^P + |\mathrm{PDIN}(i)|^P\right)^{1/P}.$$

Using a Boolean rule, alternative 1 is preferred to alternative 2 if

$$\mathrm{PSI}(1) \geqslant \max \mathrm{PSI}(2,C) \quad \text{and} \quad \mathrm{PCI}(1) \geqslant \mathrm{PCI}(2) \quad \text{and} \quad \mathrm{PDI}(1) \leqslant \mathrm{PDI}(2),$$

where C is a minimum level of project satisfaction required by the decision maker.

EXAMINING STRENGTHS OF GROUPINGS

For large problems, we may wish to examine how strongly groups of alternatives or criteria are related to each other when making decisions or contemplating reducing the size of the problem. Q-analysis shows which elements are related to each other in a simplex. The eccentricity ecc(σ) can be computed to show how strongly the elements in this simplex are connected.

The following equation gives the conventional measure of eccentricity [3]:

$$\mathrm{ecc}(\sigma) = \frac{q' - q^*}{q^* + 1}, \tag{7}$$

where

q' = highest q-level at which alternative σ is alone in equivalence class,
q^* = highest q-level at which alternative σ shares an equivalence class.

At low levels of satisfaction, the eccentricities are often all zero, which indicates all the alternatives are integrated. This is not surprising, since low levels of satisfaction would not distinguish many alternatives from each other. Thus, a new measure of eccentricity is presented to determine which alternatives are grouped more strongly in the case where there are no isolated alternatives in the high-q-level equivalence classes. Again, from the Q-analysis, we can visually see the groupings, but no measure has been put on the strength of this grouping.

A new eccentricity measure for nonisolated equivalence classes is proposed as follows:

$$\mathrm{ecc}'(\sigma) = \frac{\Sigma_i q_i / \sigma_i}{\frac{1}{2} q_{\max}(q_{\max} + 1)}, \tag{8}$$

where

q_i = every q-level σ appears in,
σ_i = number of elements in equivalence class at q_i,
$q_{\max}$ = maximum q-level in analysis.

The new eccentricity conveys the same information as the Q-analysis for $\alpha(k) = 0.25$. Both eccentricities show that {A8} stands alone, but the conventional eccentricity implies all other alternatives are equally connected and the new eccentricity groups {A8, A6, A7, A9} and {A2, A4, A5, A10} more strongly than the rest, as they should be. (See Table 5.)

In the equivalence-class data, A7 and A9 appear separately at higher q-levels at the higher levels of satisfaction. Thus, the two alternatives seem to satisfy the criteria equally well, although the two are not integrated with each other. In the case of the lower level of satisfaction, $\alpha(k) = 0.25$, A8 is the highest-ranking alternative. Although this does not seem to be compatible with having robust results, note that A8 has a consistently moderate ranking across all the criteria. All the other alternatives excel in some criteria and fall short in others.

It should be no surprise that the highest-ranking alternatives differ with the decision-making policy. A8 is the choice to satisfy all the criteria somewhat (policy I). A7 and A9 are the choices for achieving maximum satisfaction in a few criteria (policy II). (See Table 6.)

If an alternative has a high eccentricity, it is not well integrated with the others, and stands alone. Usually (depending on the criterion it satisfies), this is good, because it may be a deciding factor for the decision maker. However, if only one alternative out of many satisfies a particular criterion, perhaps this criterion is not useful when it comes to ranking all of the other alternatives.

TABLE 5

Q-ANALYSIS FOR THE ORIGINAL PROBLEM

$\alpha(k) = 0.25$

q	Q	Equivalence classes
7	1	{A8}
6	1	{A6, A7, A8, A9}
5	1	{A2, A3, A4, A5, A6, A7, A8, A9, A10}
4	1	{A2, A3, A4, A5, A6, A7, A8, A9, A10, A11}
3	1	{A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11}
2	1	{A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11}
1	1	{A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12}
0	1	{all}

$A \times A^T - 1$

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	ecc(σ)	ecc′(σ)
A1	3	3	3	2	2	3	3	3	3	3	3	−1	0	.0062
A2		5	4	3	4	5	5	5	5	5	4	−1	0	.0403
A3			5	3	4	5	5	5	5	4	4	0	0	.0062
A4				5	3	4	4	5	4	3	2	1	0	.0403
A5					5	5	5	5	5	4	3	0	0	.0403
A6						6	6	6	6	5	4	0	0	.0832
A7							6	6	6	5	4	0	0	.0832
A8								7	6	5	4	1	$\frac{1}{7}$	.3332
A9									6	5	4	0	0	.0832
A10										5	4	−1	0	.0403
A11											4	−1	0	.0205
A12												1	0	.0030

$\alpha(k) = 0.50$

q	Q	Equivalence classes
5	2	{A7} {A9}
4	1	{A3, A7, A9}
3	1	{A3, A6, A7, A8, A9, A11}
2	1	{A1, A2, A3, A6, A7, A8, A9, A10, A11}
1	1	{A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12}
0	1	{all}

TABLE 5 *Continued.*

$A \times A^T - 1$

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	ecc(σ)	ecc′(σ)
A1	2	2	2	1	0	2	2	1	2	1	2	−1	0	.0204
A2		2	2	1	0	2	2	1	2	1	2	−1	0	.0204
A3			4	1	0	2	3	1	4	1	3	0	0	.1492
A4				1	0	1	1	0	1	0	1	−1	0	.0056
A5					1	0	1	0	0	0	0	−1	0	.0056
A6						3	3	2	3	2	2	−1	0	.1492
A7							5	2	4	2	2	0	.2	.1492
A8								2	2	2	1	−1	0	.0056
A9									5	2	3	0	.2	.1492
A10										2	1	−1	0	.0204
A11											3	−1	0	.1492
A12												1	0	.0056

$\alpha(k) = 0.75$

q	Q	Equivalence classes
4	2	{A7} {A9}
3	2	{A7} {A9}
2	1	{A2, A3, A6, A7, A9, A11}
1	1	{A2, A3, A5, A6, A7, A9, A11, A12}
0	1	{A1, A2, A3, A4, A5, A6, A7, A9, A11, A12}
−1	1	{all}

$A \times A^T - 1$

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	ecc(σ)	ecc′(σ)
A1	0	0	0	0	0	0	0	−1	0	0	0	−1	0	0
A2		2	1	0	0	1	2	−1	2	0	2	−1	0	.0458
A3			2	0	0	0	1	−1	2	0	1	0	0	.0458
A4				0	0	0	0	−1	0	0	0	−1	0	0
A5					1	0	1	−1	0	0	0	−1	0	0
A6						2	2	−1	1	0	1	−1	0	.0458
A7							4	−1	2	0	2	−1	$\frac{2}{3}$	.7458
A8								−1	−1	−1	−1	−1	∞	0
A9									4	0	2	0	$\frac{2}{3}$	.7458
A10										0	0	−1	0	0
A11											2	−1	0	.0458
A12												1	0	0

TABLE 6

Policy I ranking	Policy II ranking
A8	A7
A7	A9
A9	A3
A6	A6
A2	A11
A3	A2
A4	A5
A5	A12
A1	A1
A10	A4
A11	A10
A12	A8

We can deem such a criterion to be *inflexible*, since it is very sensitive to the choices of alternatives.

Another approach to this problem is to examine the set of alternatives. If there are not enough alternatives to satisfy a criterion for the decision maker to get a robust ranking, these alternatives may be inadequate and others should be sought.

ELECTRE I ANALYSIS

The ELECTRE I algorithm is performed on the quantified project impact matrix. The algorithm is described in [6]. Results are presented for different levels of p and q. Here p is the minimum level of concordance for which the concordance index $C(j,k)$ measures how much alternative j is preferred to alternative k. As p approaches 1, decision makers approach unanimity. q is the maximum tolerance of discordance for which the discordance index $D(j,k)$ measures how much dissatisfaction is felt by the decision maker when alternative k is chosen over alternative j. As q approaches 1, decision makers have a high tolerance for discordance.

We have

p	q	Nondominated solutions
.95	.1	{A3, A4, A7, A8, A9, A11, A12}
.9	.2	{A3, A7, A8, A9, A11, A12}
.8	.3	{A3, A7, A9, A11, A12}
.7	.4	{A3, A7, A9, A11, A12}
.6	.5	{A3, A7, A9}

The rankings are established by analyzing other combinations of p and q to see which alternatives drop out of the nondominated sets. The ranking of the best three alternatives in descending order is A7, A9, and A3.

INDEX FOR ANALYZING CRITERIA BY Q-ANALYSIS

If the measure of a criterion for all the alternatives in a system is the same, then this criterion is not useful in distinguishing the alternatives from each other. One index, the criterion satisfaction index CSI(i), can be obtained from the incidence matrix:

$$\mathrm{CSI}(i) = \sum_{(i,k)} w(i)b(i,j)\alpha(k), \tag{8}$$

and we reject if

$$\mathrm{CSI}(i) = 0 \qquad \text{(no alternatives are satisfied)},$$
$$\mathrm{CSI}(i) = \sum_k I \cdot \alpha(k) \qquad \text{(all alternatives satisfied)},$$

where I is the total number of alternatives. Acceptable values for this CSI are thus around 0.5.

TABLE 7

Project impact matrix—quantified (transpose)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
C1	0.71	0.73	0.73	0.22	1.34	0.63	1.51	0.67	0.42	0.54	0.45	0.00
C2	0.40	0.30	0.95	0.60	0.60	0.60	0.70	0.50	0.90	0.40	0.10	1.00
C3	0.60	0.90	0.60	0.61	0.51	0.99	1.00	0.50	0.80	0.50	0.95	0.05
C4	0.35	0.55	0.70	0.50	0.52	0.55	0.58	0.60	1.00	0.53	0.75	0.10
C5	0.96	0.99	0.80	0.80	0.80	0.95	0.99	0.70	0.90	0.75	0.92	0.01
C6	0.40	0.48	0.30	0.50	0.60	1.00	1.00	0.70	0.80	0.65	0.30	0.90
C7	0.17	0.11	0.17	0.33	0.17	0.17	0.17	0.33	0.17	0.17	0.08	1.00
C8	0.68	0.80	0.95	0.55	0.20	0.60	0.80	0.60	0.83	0.70	0.99	0.50

Preference matrix

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
C1	0.68	0.70	0.72	0.00	1.00	0.55	1.61	−1.31	0.30	0.64	0.41	0.00
C2	0.29	0.22	1.00	0.66	0.37	0.52	0.64	−0.65	0.88	0.40	0.02	1.00
C3	0.54	0.90	0.55	0.67	0.29	0.99	1.00	−0.65	0.76	0.57	0.96	0.05
C4	0.23	0.50	0.68	0.48	0.30	0.46	0.49	−1.04	1.00	0.62	0.74	0.10
C5	1.00	1.00	0.81	1.00	0.54	0.94	0.99	−1.42	0.88	1.00	0.92	0.01
C6	0.29	0.42	0.17	0.48	0.37	1.00	1.00	−1.42	0.76	0.83	0.24	0.90
C7	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
C8	0.65	0.78	1.00	0.57	0.03	0.52	0.76	−1.04	0.80	0.91	1.00	0.50

TABLE 8

$\alpha(k) = 0.25$

q	Q	Equivalence classes
9	2	{C3, C5} {C8}
8	3	{C1, C3, C4, C5} {C2} {C8}
7	1	{C1, C2, C3, C4, C5, C6, C8}
6	1	{C1, C2, C3, C4, C5, C6, C8}
5	1	{C1, C2, C3, C4, C5, C6, C8}
4	1	{C1, C2, C3, C4, C5, C6, C8}
3	1	{C1, C2, C3, C4, C5, C6, C8}
2	1	{C1, C2, C3, C4, C5, C6, C8}
1	1	{C1, C2, C3, C4, C5, C6, C8}
0	1	{C1, C2, C3, C4, C5, C6, C7, C8}
−1	1	{all}

$A \times A^T - 1$

	C1	C2	C3	C4	C5	C6	C7	C8	ecc(σ)	ecc′(σ)
C1	8	6	8	7	8	6	−1	7	0	0.1333
C2		8	7	6	7	7	0	7	0.125	0.2667
C3			9	8	9	7	0	8	0	0.2333
C4				8	8	6	−1	7	0	0.1333
C5					9	7	−1	8	0	0.2333
C6						8	0	7	0.125	0.2667
C7							0	0	0	0
C8								9	0.25	0.4667

$\alpha(k) = 0.50$

q	Q	Equivalence classes
9	2	{C5} {C8}
8	1	{C3, C5, C8}
7	1	{C3, C5, C8}
6	2	{C1} {C3, C5, C8}
5	1	{C1, C2, C3, C4, C5, C6, C8}
4	1	{C1, C2, C3, C4, C5, C6, C8}
3	1	{C1, C2, C3, C4, C5, C6, C8}
2	1	{C1, C2, C3, C4, C5, C6, C8}
1	1	{C1, C2, C3, C4, C5, C6, C7, C8}
0	1	{all}
−1	1	{all}

TABLE 8 *Continued.*

$A \times A^T - 1$

	C1	C2	C3	C4	C5	C6	C7	C8	ecc(σ)	ecc′(σ)
C1	6	2	5	2	6	2	−1	5	.1667	.1873
C2		0	—	—	0	—	—	0	0	.0540
C3			4	2	4	2	—	1	0	.2095
C4				4	4	3	—	0	0	.0540
C5					10	7	—	2	.1111	.4095
C6						8	—	0	0	.0317
C7							—	—	0	0
C8								3	.1111	.4095

$\alpha(k) = 0.75$

q	Q	Equivalence classes
8	1	{C5}
7	1	{C5}
6	1	{C5}
5	1	{C5, C8}
4	2	{C3, C5, C8} {C6}
3	2	{C3, C5, C8} {C6}
2	3	{C2} {C3, C5, C8} {C6}
1	4	{C1} {C2} {C3, C5, C8} {C6}
0	1	{C1, C2, C3, C4, C5, C6, C7, C8}
−1	1	{all}

$A \times A^T - 1$

	C1	C2	C3	C4	C5	C6	C7	C8	ecc(σ)	ecc′(σ)
C1	1	−1	0	−1	0	0	−1	0	1	.0278
C2		2	0	0	1	1	0	1	2	.0833
C3			4	0	4	2	−1	3	0	.0926
C4				0	0	0	−1	0	0	0
C5					8	3	−1	5	.5	.7454
C6						4	0	2	4	.2778
C7							0	−1	0	0
C8								5	0	.1620

The Q-analysis for the conjugate complex is shown in Table 7. This analysis is performed to examine the relationship between the criteria. The transpose of the original problem is taken, yielding an 8×12 preference matrix.

The MCQAII analysis follows the same procedure and ranks the criteria in the following order (1 = least important, 3 = most important):

Rank	Criteria	PRI1	Original weight
1	C5	0	1
2	C8	1.039	2
3	C2	1.182	2
4	C6	1.231	1
5	C3	1.242	3
6	C1	1.248	3
7	C4	1.562	3
8	C7	1.943	1

Here we see that, based on these alternatives, some of the criteria of lesser importance may be the most useful in distinguishing the alternatives for their ranking. The eccentricities shown in Table 8 are computed to measure the integration of a simplex of criteria into the overall complex.

In the equivalence-class data, C7 (learning curve) looks like the least important criterion for discriminating between alternatives. It appears at q-level 0, so it is not well integrated with the rest of the criteria used to rank the alternatives.

C5, C8, C3, and C6 appear at high satisfaction levels, so they should be carefully considered in further analysis. A proposed ranking of criteria in descending order of criterion values and q-analysis grouping is C5, C8, C3, C6, C1, C2, C4, C7.

RESULTS

The complete MCQAII output (the short list) is in Appendix A of [4]. In Table 9, alternatives are ranked in descending order of PRI1.

The project rating indices PRI1 and PRI2 are computed with $p = 1$. As p increases in value (towards infinity), the ranking selects the shortest distance between the vector of indices and the ideal point. With the payoff matrices used, however, the ranking is not as clear cut for $p = 1$ as for $p = 2$. There are several equal values of rating indices due to computational roundoff.

TABLE 9

	Moderate ($\alpha = 0.1$), $p = 1$		Sparse ($\alpha = 0.25$)		Dense ($\alpha = 0.05$)	
Rank	PRI1	PRI2 [a]	PRI1	PRI2	PRI1	PRI2
1	9	9	9	9	9	9
2	7	7	7	7	7	7
3	3	3	12	3	3	3
4	12	11	3	11	11	11
5	11	6	11	6	6	6
6	6	2	6	2	2	2
7	2	8	2	1	8	8
8	5	1	8	8	1	1
9	8	10	5	5	10	10
10	1	5	1	10	5	5
11	10	12	10	4	12	12
12	4	4	4	12	4	4

[a] Discordance.

The highest-ranking alternative in all the tests is A9, automated presolder inspection, followed by A7, component insertion. The next best group of alternatives is A3 and A11. A more mediocre group is A6, A2, and A8. The alternatives A5, A1, A10, and A4 are the least preferred. In the MCQAII program the option of doing nothing (select no automation project), A12, surprisingly ranks very high in some tests and very low in others. The Q-analysis, however, always shows that it is integrated at low levels of satisfaction. The results are similar for the ELECTRE I analysis. The highest-ranking alternatives are A7, A9, A3, A11, and A12. Here again, the option of selecting no automation project ranks higher than the other alternatives.

To get a more robust ranking of alternatives, perhaps different projects (with the exception of A9, A7, A3, and A11) should be considered, since those considered do not rate much higher than doing nothing. It would be beneficial to propose, if possible, projects which satisfy more of the criteria at high levels.

DISCUSSION

In a realistic manufacturing setting, it is unlikely that one automation project alone would bring dramatic improvements to the facility. Even when the project is implemented flawlessly, a bottleneck usually arises in the next process, and the automated process is left idle far below capacity to control the work in process inventory. Thus, unless an entire system is implemented incorporating the most favorable alternatives, investment in a single alternative may not enhance productivity and competitiveness as much as predicted.

In the PCB example the eccentricities of A9, A7, A3, and A11 show that this would be a good group to implement.

The conjugate-complex analysis is used to rank the criteria for a given set of alternatives. Although the set of criteria may be the same when evaluating future automation projects, the ranking of the criteria will probably change with the choices of alternatives. It is common for new alternatives to satisfy new criteria which the old alternatives must be evaluated against.

CONCLUSIONS

MCQAII has been used to analyze automation investment projects by a set of quantifiable and nonnumeric criteria, with results comparable to the ELECTRE I analysis. The decision maker can choose alternatives that optimize long-term strategies such as flexibility, quality, and competitiveness even though these do not seem like cost effective strategies in the short term. The use of a multicriterion decision-making tool is valuable to managers who accept that there are other criteria to satisfy which sometimes conflict with the traditional short-term ones.

This tool allows managers to compare alternatives by analyzing how well they satisfy an entire set of criteria. Policy decisions determine the numerical satisfaction levels for the analysis and policy must determine whether the best alternative meets a minimum satisfaction level for as many criteria as possible or achieves the highest satisfaction level for a subset of the criteria.

By generating the conjugate complex, decision makers can analyze the ranking of criteria for a particular set of alternatives. The dominating criteria and equivalence classes should be examined. Are decisions based on this criterion set acceptable and in concordance with strategic objectives? This is where decision makers check to see that the alternative choices utilize the nonnumerical long-term criteria as well as the quantifiable short-term criteria.

The new measure of eccentricity in the Q-analysis can group the alternatives and give a measure of connectivity. This gives the decision maker more information for considering a set of alternatives and criteria to maximize satisfaction, as opposed to choosing only the highest-ranked alternative.

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